

OSCILLATORY DYNAMICS OF SINGLE BUBBLES AND AGGLOMERATION IN A SOUND FIELD IN MICROGRAVITY

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ABSTRACT

A dual-frequency acoustic levitator containing water was developed for studying bubble and drop dynamics in low gravity. It was flown on USML-1 where it was used in the Glovebox facility. High frequency (21 or 63 kHz) ultrasonic waves were modulated by low frequencies to excite shape oscillations on bubbles and oil drops ultrasonically trapped in the water. Bubble diameters were typically close to 1 cm or larger. When such large bubbles are acoustically trapped on the Earth, the acoustic radiation pressure needed to overcome buoyancy tends to shift the natural frequency for quadrupole ($n = 2$) oscillations above the prediction of Lamb's equation. In low gravity, a much weaker trapping force was used and measurements of $n = 2$ and 3 mode frequencies were closer to the ideal case. Other video observations in low gravity include: (i) the transient reappearance of a bulge where a small bubble has coalesced with a large one, (ii) observations of the dynamics of bubbles coated by oil indicating that shape oscillations can shift a coated bubble away from the oil-water interface of the coating giving a centering of the core, and (iii) the agglomeration of bubbles induced by the sound field.

INTRODUCTION

A. Background and Motivation

Acoustic standing waves have long been used as a method for trapping very small bubbles in liquids in a normal gravitational field (1g). Early descriptions of this trapping are summarized in Refs. 1 and 2 and most applications of the technique to the study of bubble dynamics concern the trapping by acoustic radiation pressure of very small bubbles (typically $<100 \mu\text{m}$ in radius) at the pressure antinode of the standing wave.³ For reasons described in Ref. 1 and reviewed in Sec. I, bubbles larger than a critical size determined by the acoustic frequency are pushed away from pressure antinodes and are attracted to the pressure nodes of a standing wave. This attraction to pressure nodes (due to the radiation pressure or average force on a bubble) is important to the experiments to be summarized since we are primarily concerned with bubbles larger than the aforementioned critical size associated with the

monopole resonance of a bubble. For the ultrasonic frequencies used in the flight apparatus (see Sec. II) the resonant radius R_0 was approximately 150 μm or 50 μm , depending on which acoustic mode of the levitator was driven.

Shape Oscillations: One of the objectives of the flight experiments was to study the dynamics of shape oscillations of bubbles in which the principal restoring force results from surface tension. In the absence of buoyancy and acoustic radiation stresses, the bubble has a spherical shape. Lamb predicted that in the absence of viscous dissipation, the natural frequency for the n th order shape oscillation mode is given by⁴

$$f_n = \frac{1}{2\pi} \left\{ \frac{\sigma n(n+1)(n-1)(n+2)}{R^3 [n\rho_o + (n+1)\rho_i]} \right\}^{1/2}, n \geq 2 \quad (1)$$

where R is the bubble radius, σ denotes the surface tension, ρ_o is the density of the outer medium (water), and ρ_i is the density of the inner gas (air). For example, if $R = 5 \text{ mm}$, then the frequency of the quadrupole shape oscillation mode of a bubble in water is predicted to $f_2 = 13.2 \text{ Hz}$. In this example, and even for much smaller bubbles, the frequencies predicted by Eq. (1) are generally so low that direct coupling of an acoustic wave of frequency f_n is impractical as well as weak because the acoustic wavelength is very much larger than bubble size. An alternate acoustic method of exciting shape oscillation on bubbles based on the low-frequency modulation of ultrasonic radiation stresses was proposed by Marston^{5,6} as part of an investigation of radiation-pressure excitation of oscillations of drops.⁷ One complication to the investigation of such modes on the Earth is that the acoustic radiation stresses needed to counteract the buoyancy can be sufficient to significantly distort the equilibrium shape of a bubble. Preflight experiments⁸ (reviewed in Sec. I) demonstrated that this is greater for large bubbles where oscillations are slow and (as reviewed below) effects of viscous dissipation are weakest. One complication of static distortion is that different azimuthal modes for a given n are no longer degenerate but are usually closely spaced.

The viscosity of the liquid surrounding the bubble as well as that of the gas dissipates the energy of shape oscillations. The presence of surfactants on the bubble can cause additional dissipation as well as a shift of the surface tension σ . One effect of dissipation is to broaden the resonance peaks of different values of the mode index n such that the resonances are less distinct for small bubbles.⁵ Dissipation also causes the decay in the amplitude of freely oscillating bubbles.^{5,9} For the investigation of modal properties based on either steady-state resonance features or on free decay, it can be advantageous to consider bubbles larger than approximately 1 mm diameter. For bubbles that have

clean interfaces and are not much smaller than 1 mm, the mechanical quality factor or Q of a bubble shape oscillation mode is predicted to vary approximately as^{5,8} $R^{1/2}$ where R is the bubble radius.

Bubble Agglomeration and Coalescence: Consider now the dynamics of bubbles in an unmodulated ultrasonic field such that shape oscillations are not being driven. The primary effect of the acoustic field is to cause an attraction to special locations in the standing wave as noted earlier. This manifestation of the radiation force is sometimes referred to as the primary Bjerknes force.^{10,11} As a result of this force, bubbles in different regions of an acoustic standing wavefield should, depending on their size, tend to agglomerate at pressure nodes or antinodes.¹ Depending on their size, the agglomeration of bubbles may be enhanced by a mutual force of attraction that results from a type of acoustic radiation pressure of a wave by one bubble on a neighboring bubble. This is known as the secondary Bjerknes force and for small bubbles varies approximately as x^{-2} where x is the distance between the centers of the bubbles.^{10,11} Detailed experimental investigation of this secondary force have been carried out primarily with very low frequency pressure variations.¹⁰ The agglomeration of bubbles in low gravity in response to both the primary and secondary Bjerknes forces may be of practical value in microgravity since it may facilitate the collection and removal of bubbles from liquids. This may prove useful for experiments in fluid dynamics where bubbles can be a complication or in processes involving freezing or crystallization from solutions where bubbles are undesirable.

As a consequence of agglomeration, the liquid film separating adjacent bubbles may break giving rise to coalescence. The dynamics of this process is of general interest in physical oceanography and in ocean acoustics because of the importance of bubbles to air-sea exchange processes and to ambient noise. For the case in which one of the bubbles is much smaller than the adjacent bubble, some of the dynamics can be anticipated by considering the oscillations on a bubble with an initial bulge off to one side. The evolution of the resulting capillary wave traveling around the surface of the bubble is complicated by the dispersive character of capillary waves. Longuet-Higgins¹² has given an approximate analytical solution to the surface evolution when the initial deviation from a spherical shape is a Gaussian function of the polar angle. The analysis, which neglects viscosity, predicts repeated appearances of bulges at both the original site of coalescence and the opposite pole. Since the analysis neglects viscous dissipation, experiments are merited to confirm the presence of such transient bulges for real liquids.

An additional aspect of coalescence concerns the possible effects of surfactants. It is not easy to anticipate if surfactants should always inhibit coalescence through the stabilization of the film between adjacent bubbles or whether there can be cases where coalescence is enhanced.

Core Centering of a Bubble: There has been ongoing interest in a core-centering mechanism reported by Lee *et al.*¹³ and in subsequent experiments. Theoretical investigations indicate that the

centering of the core occurs in response to shape oscillations of the surrounding liquid shell as a result of Bernoulli's law.¹⁴ The emphasis has been on situations where air is the outermost fluid. There appears to have been no observation reported for the case of the core being a gas bubble with the outermost fluid being a liquid separated from the bubble by an immiscible liquid. Microgravity provides an excellent opportunity to investigate such a system since the density of the coating (silicone oil in the experiment performed) need not be matched with that of the outer liquid (water).

B. Summary of Flight Objectives

From the above considerations and from experiments in 1g carried out during the development of the flight hardware, objectives for the flight experiments were formulated that may be summarized as follows: (a) investigate the shape oscillation modes of bubbles for comparison with experiments carried out in 1g; (b) look for the agglomeration of bubbles in an ultrasonic standing wave without the complication of gravitational buoyancy; (c) investigate the coalescence with a large bubble; (d) investigate the effects of surfactant injection; and (e) look for core-centering in response to shape oscillations on the oil shell around a bubble core.

I. PREFLIGHT EXPERIMENTS AND APPARATUS DESIGN

A. Ultrasonic Trapping of Large Bubbles in Rectangular Chambers

An approximation that has long been used for insight concerning the trapping of bubbles in a standing wave is to approximate the radiation pressure or primary Bjerknes force as^{2,10}

$$F(x, y, z) \approx -\langle V(t) \nabla p_a(x, y, z, t) \rangle \quad (2)$$

where x , y , and z are spatial coordinates, $V(t)$ denotes the oscillating volume of the bubble, $\langle \rangle$ is a time average, and p_a is the pressure of the incident acoustic standing wave evaluated at the position of the bubble center but neglecting the presence of the bubble. An alternate approach, evaluation of projections of the acoustic radiation stress on the bubble's surface,⁶ is known to reduce to a similar final result for small bubbles in an appropriate limit.¹⁵ The bubble has a monopole resonance that affects the phase relationship between V and p and the sign of F . For the purposes of the present discussion it is sufficient to use the simplest approximation for the resonant bubble radius^{1,2,11}

$$R_0 = (3p_\infty \gamma / \rho_0)^{1/2} / 2\pi f_a \approx 3.2 \text{ mm} / f_a (\text{KHz}) \quad (3)$$

where f_a is the acoustic frequency, $p_\infty \approx 1 \text{ atm}$ is the static pressure, ρ_0 is the density of water and γ is the effective polytropic exponent of the gas in the bubble. (For a bubble contained in a closed levitation chamber, R_0 may be shifted from this value; however, that is not central to the general design considerations that follow.) The response phase for bubble radii $R < R_0$ is such that when p_a is large

$V(t)$ is small so F is directed toward pressure antinodes as for conventional acoustic levitation of small bubbles.³ For the large bubbles studied in low gravity $R > R_0$ and the sign of F is reversed, being directed toward pressure nodes. Experiments carried out in 1g confirm the attraction of large bubbles to velocity antinodes but the levitation position is offset from the antinode due to buoyancy.⁸ The experiments showed that it is possible to trap bubbles in 1g having diameters as large as 12 mm with a 22 kHz standing wave in a rectangular chamber. The general magnitude of the required acoustic pressure amplitude was comparable to 1 atm. It is noteworthy that for large bubbles significant deviations from Eq. (2) may be anticipated and the radiation force may be calculated from the distribution of acoustic radiation stresses on the surface of the bubble including dipole scattering in the analysis.

Rectangular levitation chambers had been previously developed for the purpose of studying the shape oscillations of oil drops in water.^{16,17} The flight chamber, Fig. 1, differs from ones used for ground-based studies of bubble dynamics^{8,18} primarily in the capping of the chamber with a Plexiglas plate for containment of the water. As described in Ref. 8, the ultrasonic wave is excited by a piezoelectric ceramic transducer coupled by a metal plate to the chamber.

B. Shape-Oscillations Observed in 1g

In 1g, bubbles with R from 0.8 mm to 6 mm were trapped slightly above the principal centrally located velocity antinode (or pressure node) of a rectangular levitation cell in a 22 kHz standing wave.⁸ The larger bubbles clearly had an oblate equilibrium shape that may be qualitatively understood as follows. Since the bubble lies close to a velocity antinode, the relative velocity from the acoustic wave is large near the equator of the bubble and the average pressure there is reduced relative to the average pressure at the poles of the bubble. The flattening of the bubble predicted by this qualitative consideration is in agreement with the sign predicted by an analysis in Ref. 6. Notice that the response is analogous to the levitation of drops in air that also become oblate close to velocity antinodes.^{6,19}

Shape oscillations are induced by modulating the amplitude of the drive voltage at the desired oscillation frequency f_m so that the voltage applied to the transducer is⁸

$$v(t) = v_T [1 + M \cos(2\pi f_m t)] \cos(2\pi f_s t) \quad (4)$$

where $0 \leq M \leq 1$ and M determines the modulation level. The procedure for determining the frequency of the quadrupole or $n = 2$ mode of a bubble involves tuning f_m to maximize the response of the mode.⁸ Figure 2 compares predictions based on Lamb's equation, Ea. (1), with measurements obtained by this procedure. The measurements taken in 1g are discussed in Ref. 8 and the important result is that there is a significant deviation from Eq. (1) for large bubbles. One correction used in Fig. 2 was to plot the radius as that of a spherical bubble having the same volume as the oblate levitated

bubble, however, that correction is inadequate to explain the deviation. The deviation appears to be a consequence of the large acoustic radiation stresses needed in 1g to counteract buoyancy.

C. Apparatus Design for the Experiment on USML-1

The acoustic frequencies f_a that produced standing waves of significant amplitude in the rectangular chamber were investigated and it was found that in addition to f_a near 21 kHz, appreciable standing waves could be achieved for f_a close to 63 kHz. (The precise values for f_a depended on the height of the water and the temperature.) Measurements indicated that the nodes and antinodes of the higher frequency standing wave were more closely spaced than the 22 kHz pattern shown in Ref. 8. To provide an alternative radiation pressure distribution a dual-frequency electronics driver (and modulator) was designed that is diagrammed in Fig. 3. Tests made in simulated low gravity on KC-135 flights with a prototype levitation chamber suggested that the ability to drive the transducer at about 63 kHz may be useful for stable trapping of bubbles in low gravity. Consequently, the extra complication to allow for carrier frequencies at $f_a = f_0 \approx 21$ kHz and $f_a = 3f_0$ was appropriate as was subsequently verified on USML-1. A digital display could be switched to measure either the modulation frequency f_m or to give a measure of the current delivered to the output power amplifier. The switch was located at the base of the levitator. Tuning f_a to maximize the current increases the amplitude of the ultrasonic wave. The DC voltage supply for the circuit was supplied by the Glovebox.

The inner dimensions of the Plexiglas box forming the top of the levitation chamber were 3.5 in. x 3.5 in. x 2.75 in. giving a volume of 552 cm³. The actual volume available for water was slightly larger due to a narrow gap, sealed by an O-ring, between the box and the aluminum base and because water wetted a gap between the cylindrical transducer and the base. The walls and top of the chamber were transparent so that the dynamics of bubbles could be recorded with a Glovebox TV camera. After the sealed chamber was tested to meet safety requirements, distilled water was inserted at the Kennedy Space Center through an opening that was resealed. An air bubble was left in the chamber to allow for an anticipated expansion of water resulting from any temperature variations during the nearly 4 months prior to launch.

II. SPACELAB (USML-1) RESULTS AND DISCUSSION

The experiment was scheduled for 3 hr. 15 min. of operation on MET day 11 with only intermittent real-time down link of TV video. The experiment was operated by E. Trinh.

A. Shape Oscillation Modes of Bubbles in Low Gravity

There was sufficient air in the chamber that it was not necessary to inject air through the septum except for experiments described in Sec. II.D. (Postflight measurement of the volume of air in the

chamber gave 2.4 cm^3 .) The air could be partitioned into bubbles by manual agitation of the chamber. For stable trapping of bubbles away from the sides of the chamber the frequency $f_a = 3f_0 \approx 63 \text{ kHz}$ was selected. The modulation frequency f_m was adjusted to maximize the response apparent to the operator. The size of the bubbles was measured by using the septum as a reference dimension in the video records. Real-time estimates were consistent with such measurements. Generally the equilibrium shapes of the large bubbles were far closer to spherical than when they are trapped in 1-g; the equilibrium deviation from sphericity (due to the acoustic field) being a few percent or less in low gravity.

Resonance frequencies were measured for two bubbles. Bubble 1 had a diameter $D = 14.9 \text{ mm}$ and the resonances for the $n = 2$ and 3 modes were respectively at 6.8 and 12.7 Hz . These agree with theoretical estimates from Eq. (1) of 7.2 and 13.2 Hz . Bubble 2 had $D = 8.8 \text{ mm}$ and measured $n = 2$ and 3 frequencies of 15.9 and 29.8 Hz which also agree with Eq. (1) though this bubble was trapped near the plate driven by the transducer and the plate may have perturbed that flow. The resonances for these bubbles are plotted as $+$ symbols in Fig. 2 where the frequencies are far closer to the ideal theory and any results available in 1 g for such large bubbles. The oscillation amplitudes achievable were generally smaller than for similar experiments⁸ in 1 g. This may have been a consequence of perturbation of the ultrasonic resonances of the chamber by the quality of enclosed air.

B. Bubble Agglomeration and Coalescence

Bubbles having diameters ranging from 1 to 15 mm were dispersed by agitation of the chamber. The bubbles migrated in response to the steady 63 kHz ultrasonic wave. In the recorded words of the operator, "Turning on the (acoustic) field . . . gathers them up in about the same place." Figure 4 reproduces a video record showing acoustically gathered bubbles. Video records of the migration suggest that while primary Bjerknes forces and viscous drag are most important in determining the trajectories, secondary Bjerknes attraction may also contribute in certain situations.

A remarkable feature of video records like Fig. 4 is that the bubbles, once gathered, did not tend to naturally coalesce. Nevertheless, a few coalescence events were recorded on video but it is noteworthy that these were seen within 60 seconds after a dilute surfactant was injected through a hypodermic needle at the surface of a large bubble. The solution was sodium dodecylsulphate (SDS) at 0.75 of CMC (critical micelle concentration) prior to injection. The amount of surfactant injected was such that postflight measurements of the water indicated that the surface tension σ was reduced to $63 \pm 1 \text{ dyn/cm}$.

The clearest sequence recorded shows a 2 mm radius bubble popping into a 15 mm diameter bubble with a negligible sound field present. Coalescence launches a wave that disperses and travels around the bubble. Waves converge back at the point of coalescence to produce transient bulges. The

first and strongest convergence occurs about 5 video frames (i.e. $5/30 \approx 0.17$ sec) after coalescence. The angular width of the initial bulge corresponds to the width of the small coalescing bubble and this width is close to the width of an initial Gaussian bulge considered in a calculation by Longuet-Higgins.¹² The predicted time for convergence is $1.9(R^3/\sigma)^{1/2} = 0.16$ sec where $\sigma = 63$ dyn/cm and $R = 7.5$ mm is the initial radius of the large bubble. The observed interval of 0.17 sec is close to the predicted value. Evidently, the initial condition assumed by Longuet-Higgins, in which the $n = 4$ and 5 modes were most strongly excited, well approximate the conditions for this coalescence event.

C. Shift in Bubble Modes Produced by the Surfactant

The resonance frequencies of the $n = 2$ and 3 modes were measured for a bubble with $D = 15$ mm giving respectively 6.2 and 11.9 Hz. These are close to the calculated values with $\sigma = 63$ dyn/cm from Eq. (1) of 6.7 and 12.3 Hz. The difference may partially be from a lowering of the frequency due to the additional inertia of the oscillating boundary layer near the bubble that is neglected in Eq. (1). (See e.g. Refs. 5 and 9.) Comparison with the measurements in Sec. II.A shows that the principal reduction in frequency is a consequence of the reduction in the surface tension caused by the injected SDS solution.

D. Oscillations of Compound Bubbles in Silicone Oil Drops in Water and Evidence of Core Centering

Preflight experiments in 1 g demonstrated that it was possible to coat the wall of an acoustically levitated bubble with a thin liquid layer immiscible in water. To prevent the pooling of the layer at the bottom of the bubble, it was necessary to closely match the density of the layer to that of water by mixing silicone oil and CCl_4 . This difficulty in generating such levitated coated bubbles in 1 g and interest in core centering reviewed in the introduction (A) motivated observations of the dynamics of compound bubbles on USML-1 in which the coating was pure silicone oil (Dow Corning 200) having a viscosity of 2 cS and a density of 0.87 g/cm^3 . Since the measurements were taken after the injection of the SDS surfactant, the interfacial tension with water was lower than the ideal value for clean water of about 25 dyn/cm. Silicone oil is more compressible than water and the ultrasonic mode of the levitation cell near 21 kHz was used to trap compound bubbles and drops of silicone oil in low gravity.

The most important of the observations were made with a compound bubble in which the outer diameter of the oil coating was 5 to 6 mm and the average thickness of the coating was ≈ 1 mm. For the generation of centering of the core in other liquid shell systems, the relevant mode is thought to be the "sloshing mode" in which the outer and inner surfaces move out of phase such that the shell is thickest either at its poles or its equator depending on the phase of the oscillation cycle.¹⁴ Unfortunately the resonance frequency of the sloshing mode for this system appeared to be lower (but close to) the lowest

available modulation frequency f_m of 4.5 Hz. (The apparent low frequency of this mode is supported by calculations.) Nevertheless, when f_m was reduced to 4.5 Hz, weak oscillations of the compound bubble could be seen and the enclosed bubble drifted away from the outer wall of the silicone oil shell. A video record after the drift is shown in Fig. 5(a). This is to be contrasted with the situation in the absence of modulation where the bubble tended to drift to an outer wall of the shell producing an eccentric compound bubble. Note that while only one profile view was recorded on video, the operator could view the bubble's response from more than a single profile. His recorded observations were, "(It) doesn't take much to get bubble centering in this system. Little oscillation amplitude is required." These appear to be the first observations of shape-oscillation induced core centering in a fluid system of this type where the inner fluid is gas and the outer-most fluid is liquid.

The aforementioned behavior of easy centering may be contrasted with a case where the enclosed bubble had a diameter of only 1 mm while the outer diameter of the oil drop was about 7 mm. In that case, the quadrupole mode of the drop was strongly excited giving aspect ratios as large as 2-to-1 during the oscillations. The small enclosed bubble remained at one pole of the drop showing no evidence of a core centering force, Fig. 5(b) and (c). Consequently, core centering of bubbles appears to be inhibited for bubbles that are much smaller than the surrounding drop.

E. Cavitation Plumes from an Oil Drop in Low Gravity

During the course of observations of a 2 cm diameter 2 cS silicone oil drop, an unanticipated sequence occurred. Transient acoustic cavitation at or near the surface of the drop affected the stability of the drop. The cavitation ejected a plume from the drop extending about 1 cm into the liquid. Related plumes have been photographed for drops of oil acoustically levitated in water on the Earth and the plume is thought to contain mm-sized oil drops.²⁰ In low gravity, without buoyancy the ejected mist remained in the vicinity of the drop, surrounding it after a few seconds. Subsequently the combined drop and cloud of mist became unstable in the sound field and moved out of the field of view of the camera. It is unclear whether the absence of buoyancy may have exacerbated the consequences of ultrasonic cavitation in the drop.

III. SUPPLEMENTAL OBSERVATIONS

The development and testing of the flight apparatus and supporting ground based experiments gave the first observations of large acoustically levitated bubbles. Two types of supplemental observations of the dynamics of large levitated bubbles are noteworthy. (i) Figure 6 shows oscillations of an 8 mm diameter bubble in 1 g driven by amplitude modulation of a 22 kHz ultrasonic wave. The oblate and prolate shapes have been captured by strobe lighting. On the upper surface of the bubble in each of

the pictures a capillary roughening is visible. The roughening typically has a length scale of a few 100 μm . It appears to be excited by a large amplitude ultrasonic field since the contrast in the surface usually is modulated along with the ultrasonic amplitude. The roughening is probably a manifestation of parametrically excited capillary waves. Thresholds of such waves have been previously studied for other applications.²¹ (ii) It was often possible to drive quadrupole oscillations of sufficient amplitude to break up a bubble into two bubbles. The analogous break-up of drops driven at quadrupole resonance by modulated radiation pressure has been previously reported.^{7,16,17} Neither of the processes in (i) or (ii) was observable on USML-1, probably because of insufficient sound amplitude.

Comparison of the USML-1 measurements of resonance frequencies for bubbles plotted in Fig. 2 with the theory for spherical bubbles and with the preflight measurements in 1 g illustrates an advantage of low gravity. For experiments on the Earth, to reduce the biases due to levitation field, the bubbles need to be as small as 1 to 2 mm diameter. A quantitative light scattering method was developed for measuring both the frequency and dissipation of the shape modes of such bubbles. (The method, partially summarized in Ref. 18, extends an optical extinction method previously used for drops.¹⁹) Recent measurements show that the damping of the quadrupole mode can be as low as the value calculated for an ideal clean interface between air and water.^{5,9} Furthermore, the mode properties were found to be a sensitive non-contact probe of the bubble's surface.

CONCLUSIONS

The measurements of quadrupole resonance frequencies performed in microgravity and summarized in Section II.A confirm that the strong acoustic levitation field used on the Earth can bias the resonance frequencies. As summarized in Section III, a method has been found (partially based on insight from that result) that simplifies the interpretation of measurements in 1 g. Such measurements have application to the probing of interfacial properties. Other observations in microgravity, summarized in Sections II.B - II.E illustrate various aspects of bubble dynamics without the complication of gravitationally induced buoyancy. Of these observations the following are especially noteworthy: the agglomeration of bubbles in a ultrasonic field, the observations of capillary waves induced by coalescence, and the evidence for core centering in the compound bubble system in response to shape oscillations. Ground based experiments have expanded our ability to trap bubbles as large as 12 mm diameter and, as described in Ref. 8, have advanced the development of stable levitators. During the course of this work the mechanism for exciting shape oscillations on bubbles proposed in Refs. 5 and 6 has been confirmed. Discoveries from supporting ground based investigations of the dynamics of levitated bubbles are summarized in Sections I.B and III.

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Figure 1 Photograph of the chamber of water flown on USML-1. The aluminum base of the chamber houses a piezoelectric ceramic transducer that generates an ultrasonic standing wave in the water. A 1/2 inch diameter septum on one Plexiglas wall was penetrated by needles during the experiment to facilitate the injection of fluids. The bulb on the upper left served as a ballast during the experiment but was sealed off during launch.

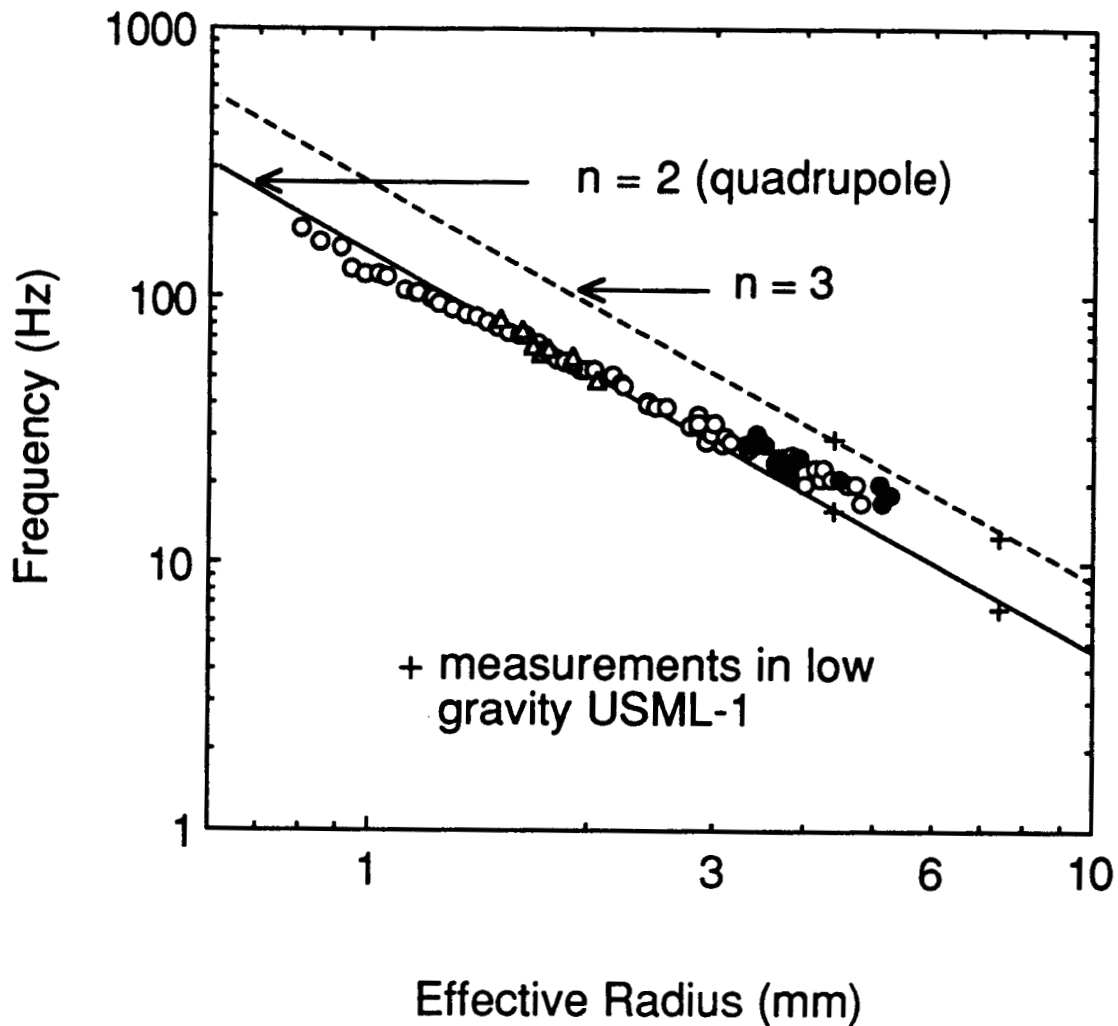


Figure 2 Preflight measurements of resonance frequencies for a wide range of bubble sizes in water are compared with measurements taken on USML-1 shown as + symbols. Also shown is the theoretical result from Eq. (1) which neglects a viscous correction that is small for large bubbles. The circles are based on maximization of the visible quadrupole response and the triangles are based on a light scattering method (see Ref. 8). In 1 g the levitation field distorts the bubbles and the circles where the equilibrium aspect ratio exceeded 1.3 are filled in. To reduce the effect of this bias, our data from Ref. 8 has been replotted here using an effective radius corresponding to that of a spherical bubble having the same volume. The USML-1 measurements (see Section II.A) were unbiased since they were taken on nearly spherical bubbles. They included observations of the $n = 3$ mode.

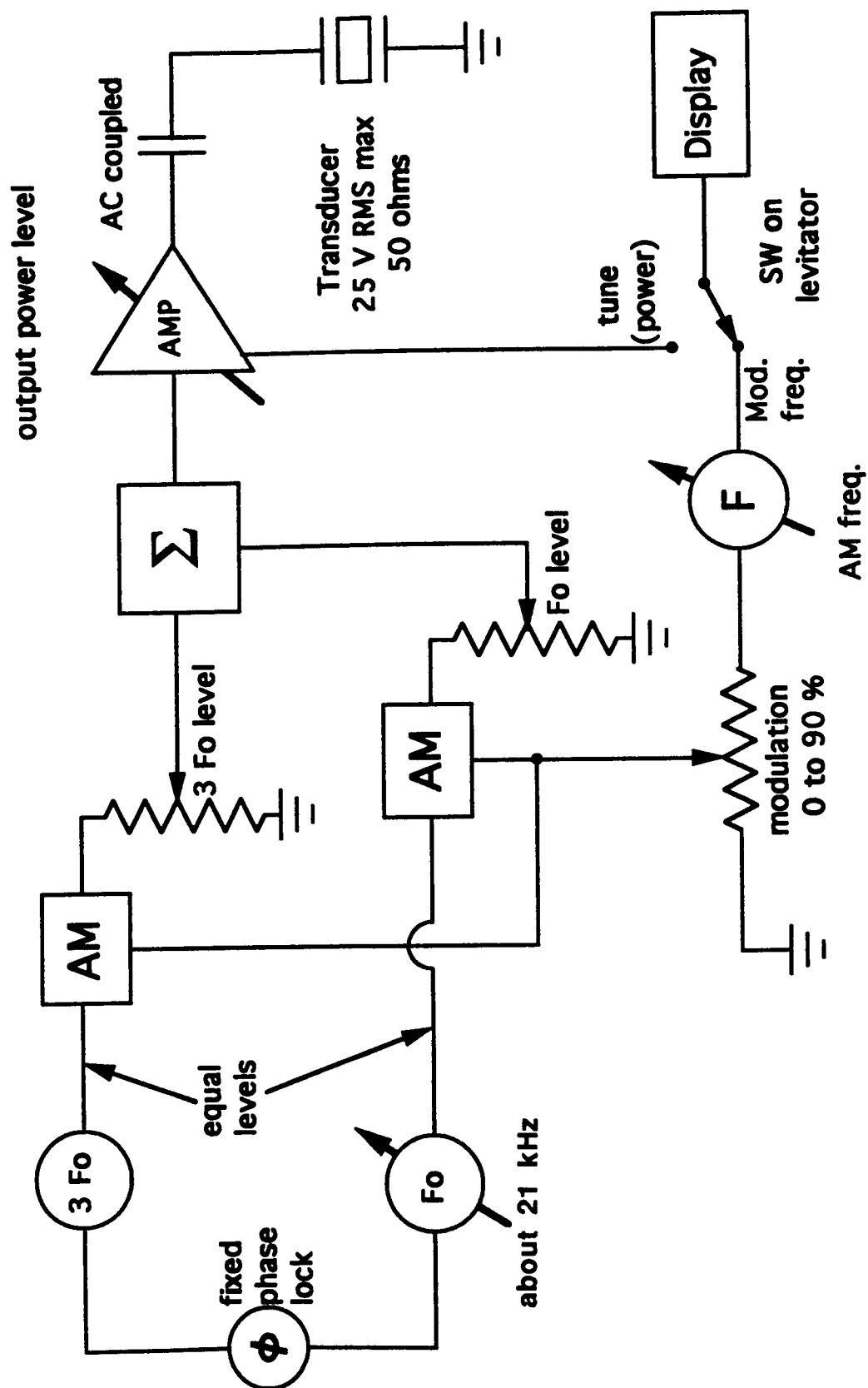


Figure 3 Circuit used to generate the modulated transducer voltages for the USML-1 experiment. The dual-frequency design enhanced the flexibility of the experiment.



Figure 4 Video record of bubbles agglomerated together in low gravity in response to a 63 kHz ultrasonic standing wave. In the absence of gravitational buoyancy, a weak ultrasonic standing wave was sufficient to induce agglomeration.



Figure 5 Low-gravity observations of a compound drop-bubble system. (a) shows a bubble contained in an oil drop in water subjected to low amplitude shape oscillations. In response to the oscillations the bubble core moves away from the wall of the drop. The density of the oil differs from the density of the surrounding water. (b) and (c) show a case where the bubble was much smaller than the drop. Prolate and oblate phases of the oscillating drop are shown. The bubble, visible at the upper end, shows no evidence of a centering force, unlike the case in (a).

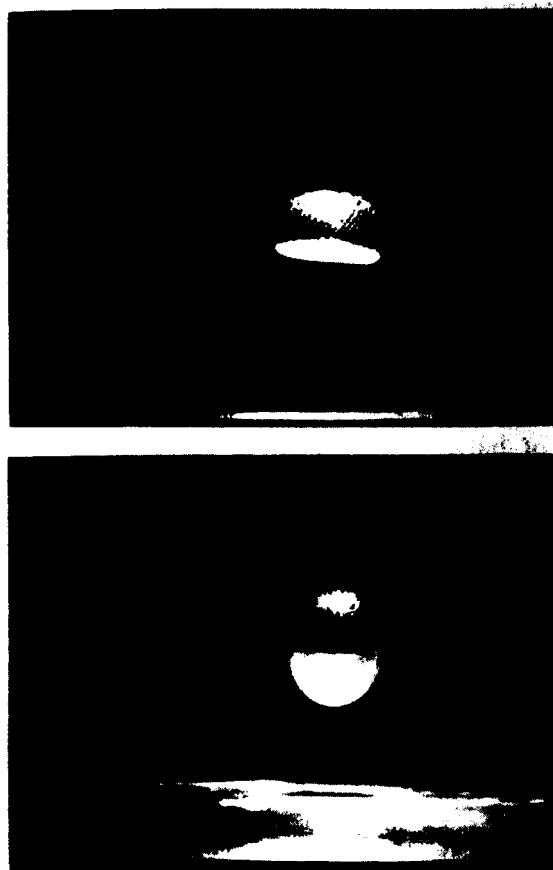


Figure 6 Oblate and prolate phases of an 8 mm diameter bubble oscillating in the $n = 2$ mode in 1 g. Capillary roughening is visible on the upper surface that is coupled to the strong ultrasonic field.